

A Proposed Mix Design for High-Volume Fly Ash-Self Compacting Concrete (HVFA-SCC)

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ABSTRACT

High-Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) is an environmentally friendly concrete type that uses a high quantity of fly ash as a partial replacement of cement by at least 50%. The use of fly ash not only increases cost efficiency but also reduces the environmental impact of cement production. During the application of HVFA-SCC, an appropriate mix design is required to ensure its compressive strength and meet the criteria of Self-Compacting Concrete (SCC). This study proposes a mix design procedure for HVFA-SCC. A concrete cylinder test with varying water contents and water-powder ratios was conducted. The water contents used were 150, 175, and 200 kg/m³, the water-powder ratio utilized was 0.3–0.7, and the replacement of cement with fly ash was 50%. The ratio between the Fine Aggregate (FA) and Coarse Aggregate (CA) was determined using the packing density approach, where the ratio was selected based on the maximum packing density value. The results showed that all test specimens exhibited adequate flowability, filling ability, and segregation resistance, as per EFNARC 2005. From the results of the compressive strength test, it was observed that a higher water-to-powder ratio led to a lower compressive strength. Based on experimental data, the study proposes an equation for the relationship between the water-powder ratio and compressive strength. This equation is used to determine the water-powder ratio according to the planned compressive strength. The proposed mix design procedure discussed in this study can be used to produce concrete with a compressive strength ranging from 18 to 47 MPa, making it a useful reference for the production of structural concrete.

Keywords-compressive strength; HVFA-SCC; mix design; packing density; water-powder ratio

I. INTRODUCTION

The construction industry continues to grow along with the demand for more environmentally friendly, economical, and high-performance materials [1-2]. One of the innovative materials under development is HVFA-SCC, which contains a high quantity of fly ash as a partial replacement of up to 50% of the cement [3]. The HVFA-SCC has several advantages, such as reduced carbon emissions, increased durability, low cost, and increased casting efficiency due to its self-compacting nature [4-7].

The mix design is an essential tool in concrete technology, which helps achieve concrete performance that meets the criteria in both fresh and hardened conditions [8]. The mix design must optimize the concrete properties, such as workability, resistance to segregation, compressive strength,

and durability. Inaccuracy in determining the composition of materials can cause problems in concrete performance, such as strength not meeting standards or segregation of the mixture, which can reduce homogeneity and structural resistance.

The efficiency of HVFA-SCC applications depends on the correct mix design. Currently, there are no established codes governing the mix design procedures for HVFA-SCC. It has been shown that for the casting of HVFA-SCC test specimens, the mix composition should be based on a trial mix or previous research [9-11]. Authors in [12] demonstrated that SCC can be produced in high volumes using fly ash, allowing the replacement of up to 60% of cement with Class F fly ash.

Authors in [13] proposed a methodology for proportioning SCC suitable for high-volume ASTM Class F fly ash content. They used a water-cement ratio obtained from a systematically

developed model, with the quantity of chemical additives and FA based on rheological requirements [14]. Furthermore, the CA quantity was calculated employing the absolute volume method. Target strength, as well as self-compacting properties of the mixture, were achieved with minimal trial. The water content was set to 170 kg/m³ for the initial trial, with the water-powder ratio kept between 0.24 and 0.36. Six SCC mixtures were designed by deploying the proposed method with varying powder and FA contents. The target compressive strength at 28 days was maintained at 45 MPa for all SCC mixtures, while the test results showed actual compressive strengths ranging from 50.5 to 66.4 MPa.

Research on concrete mix design procedures for HVFA-SCC is important to ensure that the resulting concrete meets the target compressive strength and satisfies the SCC requirements. The present experimental study proposes a mix design procedure that can be used in HVFA-SCC. Moreover, a relationship between the water-powder ratio and compressive strength is formulated, which can be used to determine the water-powder ratio for the expected compressive strength.

II. MATERIALS AND METHODS

A. Materials

The cement used in this study is Ordinary Portland Cement (OPC) produced by PT Semen Gresik Tbk, with a specific gravity of 3.15 and a volume weight of 1255 kg/m³. The fly ash used is from Paiton PLTU, with 63.15% SiO₂, 16.88% Al₂O₃, and 9.23% FeO. The former is Class F in accordance with ASTM C618-23 [16]. Furthermore, a Superplasticizer (SP) is added to meet the required the SCC properties. The SP used is Sika Viscocrete 3115N, produced from a modified Polycarboxylate Copolymer solution. Figures 1(a) and 1(b) show the appearance of cement and fly ash. The FA for concrete mix design was river sand with a maximum size of less than 4.75 mm and falls into grading zone 2 (rather coarse). The CA is machine-crushed stone, with a maximum size of 19 mm. Table I summarizes the physical parameters of FA and CA. The water used is pure, free from dirt, oil, chemicals, and organic compounds.

B. Mix Proportions

This research utilizes HVFA-SCC samples with a fly ash percentage of 50% relative to the cement weight. According to EFNARC 2005, the water content should not exceed 210 kg/m³ [15]. Similarly, the water content for SCC should be 170-176 kg/m³ for medium compressive strength [16]. Water content below 155 kg/m³ is found to be challenging to use in SCC mixes and requires a larger quantity of water-reducing admixture, making it uneconomical from a cost perspective [17]. The water content was varied at 150, 175, and 200 kg/m³, with water-powder ratios of 0.3, 0.4, 0.5, 0.6, and 0.7. SP Sika Viscocrete 3115N, produced by PT Sika Indonesia, was used to ensure flowability. The SP content was 1.2% of the cement weight. The proposed mix design approach follows SNI 7656:2012, with modifications made to meet the requirements of EFNARC (2005). The mix design includes determining the quality of concrete, water-powder ratio, concrete weight, and aggregate weight. The FA content is adjusted to meet its provisions, comprising 48–55% of the total aggregate, and the

CA content ranges between 750 and 1000 kg/m³ [18]. SNI 7656:2012 was prepared by adopting ACI 211.1-91 [19].

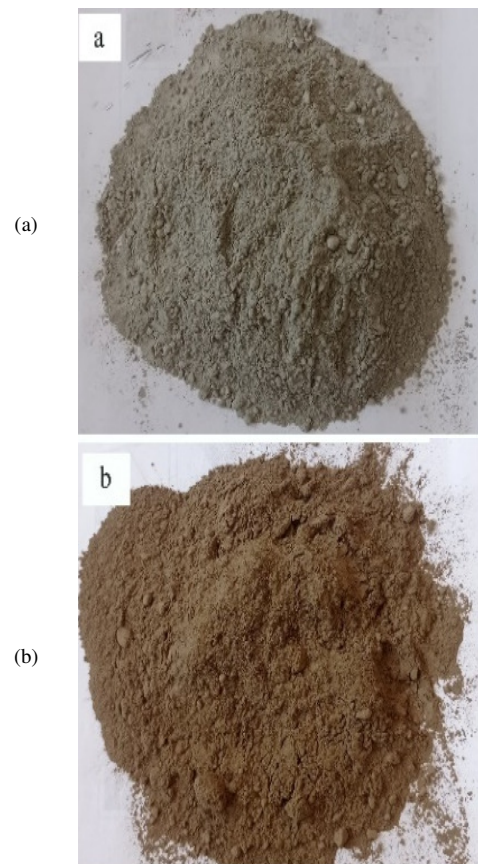


Fig. 1. Physical appearance and texture of: (a) cement, (b) fly ash.

TABLE I. PROPERTIES OF SAND AND GRAVEL

Properties	FA	CA
Weight per volume (kg/m ³)	1416	1542
Specific gravity (kg/m ³)	2.54	2.63
Mud content (%)	3.61	0.68
Absorption (%)	3.52	2.23
Fineness modulus	2.93	7.59

The packing density of an aggregate mixture is defined as the solid volume in a unit total volume. The aim of obtaining packing density is to combine aggregate particles to minimize the porosity, which allows the use of the least possible quantity of binder. The packing density can be calculated by multiplying the bulk density by the weight fraction and then dividing that number by the specific gravity [20-21]. In this research, the packing density approach is used to determine the FA to CA ratio. The specific approach was carried out by finding the combined bulk density of FA and CA with a ratio of 0.3, 0.4, 0.45, 0.5, 0.55, 0.6, and 0.7. The calculation results are depicted in Figure 2, with a maximum packing density of 73% at FA/CA of 50%. Furthermore, the FA to CA ratio was 50%. The 50% FA is in accordance with EFNARC 2005 [18], which gives a typical range between 48 and 55%.

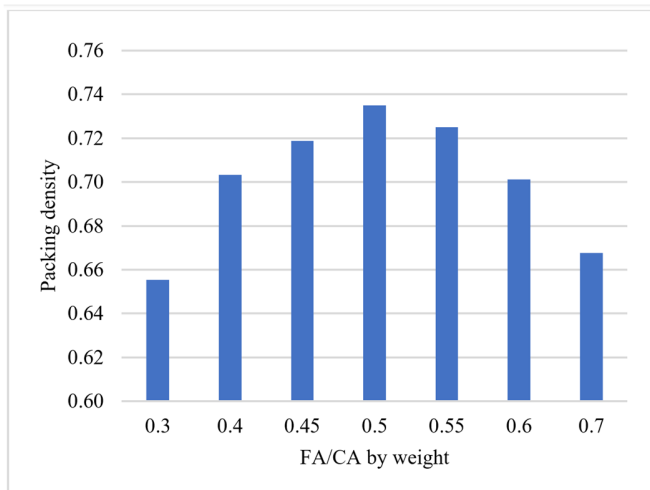


Fig. 2. FA/CA ratio versus packing density.

TABLE II. CONCRETE WEIGHT ESTIMATION

Maximum aggregate size (mm)	Concrete weight (kg/m ³)
9.50	2280
12.5	2310
19.0	2345
25.0	2380
37.5	2410
50.0	2445
75.0	2490
150	2530

TABLE III. MIX PROPORTIONS

W/P	Cement (kg/m ³)	Fly Ash (kg/m ³)	FA (kg/m ³)	CA (kg/m ³)	SP (kg/m ³)	Water (kg/m ³)
0.3	250	250	848	848	6.0	150
0.4	188	188	910	910	4.5	150
0.5	150	150	948	948	3.6	150
0.6	125	125	973	973	3.0	150
0.7	107	107	990	990	2.6	150
0.3	292	292	793	793	7.0	175
0.4	219	219	866	866	5.3	175
0.5	175	175	910	910	4.2	175
0.6	146	146	939	939	3.5	175
0.7	125	125	960	960	3.0	175
0.3	333	333	750	750	8.0	200
0.4	250	250	823	823	6.0	200
0.5	200	200	873	873	4.8	200
0.6	167	167	906	906	4.0	200
0.7	143	143	930	930	3.4	200

Concrete weight per m³ was set in accordance with the SNI 7656:2012 [22], as presented in Table II. With a maximum CA size of 19 mm, the concrete weight was 2345 kg/m³. Furthermore, the results of the mix proportion are displayed in Table III. From each composition, three concrete cylinders were made, totaling 45 samples.

C. Testing Method

Sample testing includes assessing the fresh concrete quality according to EFNARC 2005 [18] and examining the mechanical characteristics according to the ASTM standards. For the fresh concrete properties, the Slump flow test (550–850

mm), L-Box test (0.8-1), and V-funnel test (8–25 s) were carried out to assess the flowability, ability to pass through cavities between reinforcement, and SCC stability. Meanwhile, the compressive strength test was conducted in accordance with ASTM C39 [23] using concrete cylinder test specimens measuring 15 × 30 cm.

III. RESULTS AND DISCUSSION

A. Volume Weight

One day after casting the test specimens, the concrete cylinder mold was removed, and then the test specimens were treated by immersion in water. Before the compressive strength test, the specimens were dried and weighed to determine the volume weight. Figure 3 presents the volume weight of the HVFA-SCC cylinder test specimen. Figure 3 illustrates that the greater the water-to-powder ratio, the lower the unit weight. The trend also shows that the greater the water content for the mix design, the smaller the volume weight of the concrete produced. Also, the smaller the volume weight, the larger the cavities between the aggregates. The results of the concrete unit weight test revealed that the unit weight of the concrete ranged between 2227 and 2356 kg/m³.

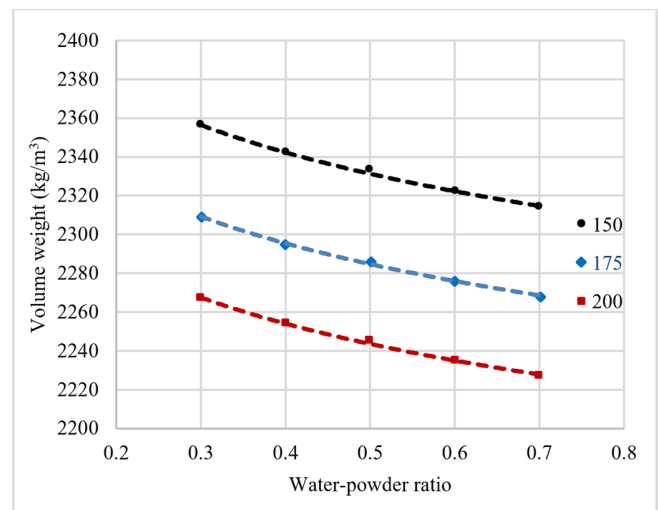


Fig. 3. Water-powder ratio versus volume weight.

B. Fresh Concrete Test

Fresh concrete was tested to ensure that the concrete mixture meets the SCC criteria. According to EFNARC 2005 [18], fresh concrete testing includes slump flow, V-funnel, and L-box testing. The SCC specifications in accordance with EFNARC 2005 are presented in Table IV. The flowability of the concrete mixture must be ensured to meet the SCC characteristic requirements. Figure 4 portrays the fresh concrete testing, while the results of the slump flow test are presented in Figure 5.

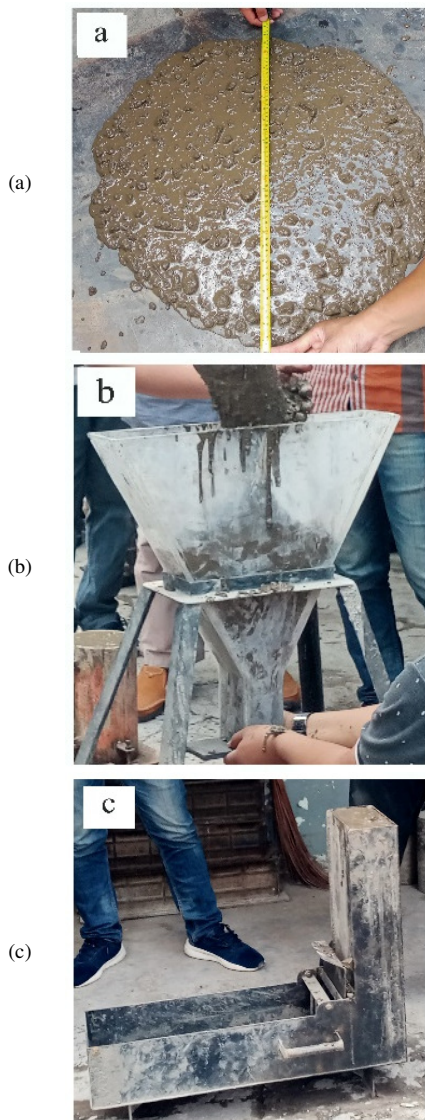


Fig. 4. Fresh concrete tests: (a) Slump flow, (b) V-funnel, (c) L-Box.

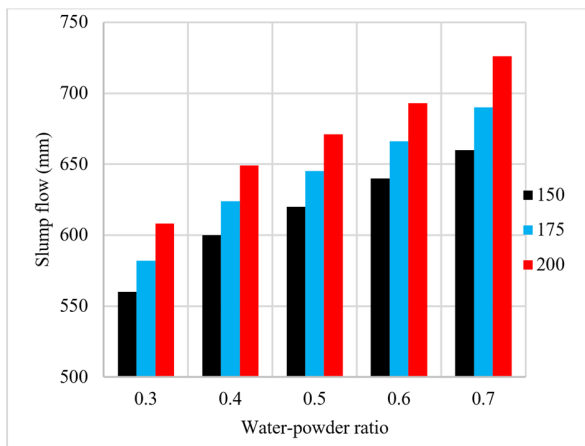


Fig. 5. Results of the slump flow test.

TABLE IV. SCC REQUIREMENTS IN ACCORDANCE WITH EFNARC 2005

Test	Unit	Requirements
Slump flow	mm	550-850
V-funnel	s	8-25
L-box	mm/mm	0.8-1.0

Figure 5 shows that the slump flow value increases as the water-powder ratio increases. The test results also show that the greater the water content per m³ of concrete, the higher the slump flow value. The slump flow values ranged from a minimum of 560 mm to a maximum of 726 mm, indicating that all test specimens met the EFNARC 2005 [18] criteria, which specify a slump flow range of 550–850 mm.

The V-funnel test was conducted to assess the viscosity and fluidity of the HVFA-SCC mixture. Figure 6 demonstrates how increasing the water-cement ratio affects the flow time of the samples. The test results show that as the water-powder ratio in the HVFA-SCC mixture increases, the V-Funnel flow time decreases. The test results also exhibit that the more the water content per m³ of concrete, the lower the V-funnel flow value. The V-funnel flow test results are between 9 and 16 s, concluding that all samples met the V-funnel flow test requirements in accordance with EFNARC 2005, which specify the range of 8-25 s.

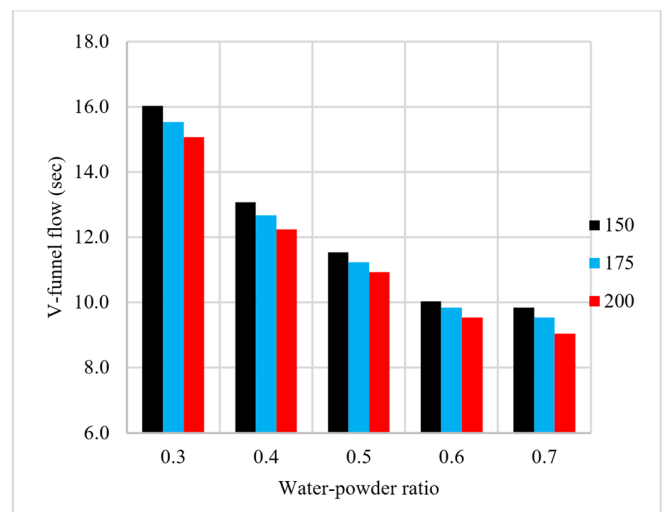


Fig. 6. V-funnel test.

The L-box test was conducted to assess the ability of the sample to pass through the cavity between the reinforcement. The optimal blocking ratio value approaching 1 indicates that the concrete can pass through the gap with minimal resistance. Figure 7 indicates that the water-powder ratio value affects the blocking ratio of the samples. The test results demonstrate an increase in the blocking ratio with an increase in the water-powder ratio. The blocking ratio for HVFA-SCC ranged from 0.81 to 0.97, indicating that all test specimens met the EFNARC 2005 requirement of 0.8-1.0.

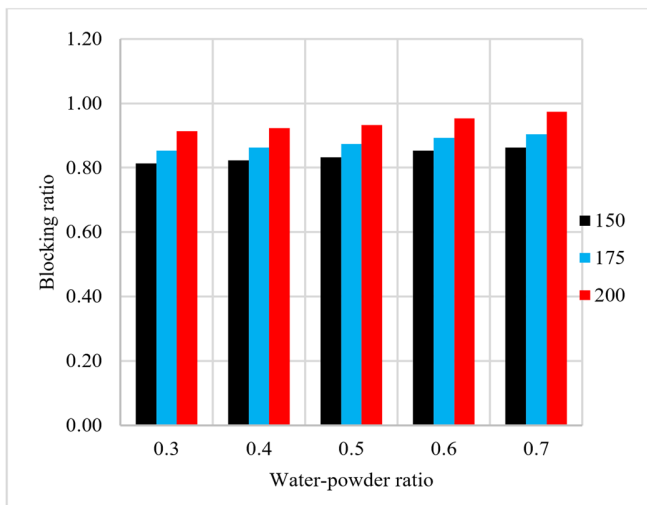


Fig. 7. Results of L-box test.

C. Compressive Strength

Concrete compressive strength testing was carried out to determine the compressive strength of concrete, in accordance with ASTM C39 [23]. The test specimens were cured for 28 days before conducting the test using a 2000 kN capacity compressive strength machine. During the test, the concrete cylinder was compressed until it was destroyed, and the working compressive force was obtained by reading the manometer of the compressive strength machine. The compressive strength was obtained by dividing the compressive force by the cross-sectional area of the cylinder. The test setup is shown in Figure 8, while the test results are presented in Figure 9.



Fig. 8. Compressive strength test setup.

Figure 9 shows that the higher the water-powder ratio, the lower the compressive strength. This result is in line with [24]. The minimum compressive strength was 18 MPa, while the maximum value was 47 MPa. Furthermore, the relationship between the water-powder ratio (w/p) and the compressive strength (f_c) can be formulated as:

- For a water content of 150 kg/m³:

$$f_c = 16.979 \left(\frac{w}{p}\right)^{-0.86} \tag{1}$$

- For a water content of 175 kg/m³:

$$f_c = 15.521 \left(\frac{w}{p}\right)^{-0.854} \tag{2}$$

- For a water content of 200 kg/m³:

$$f_c = 13.588 \left(\frac{w}{p}\right)^{-0.922} \tag{3}$$

Equations (1-3) have an R^2 value close to 1, which is around 0.99, indicating that they effectively describe the relationship between the water-to-powder ratio and the compressive strength of the concrete.

SNI 2847:2019 19.2.1. requires a minimum compressive strength of 21 MPa for Special Moment-Resisting Frame (SMRF) system structures. There is no limit on the maximum value of f_c for normal concrete except that required by specific code provisions. For the design of special moment frames and special structural walls used to resist earthquake forces, the code limits the maximum f_c of lightweight concrete to 35 MPa [25]. Figure 9 shows that the compressive strength obtained was above 21 MPa except at a water content of 200 kg/m³ and a water-powder ratio of 0.7. To ensure that the compressive strength meets the requirements for SMRF, it is proposed that when the water content is 200 kg/m³, the maximum water-to-powder ratio should be 0.6.

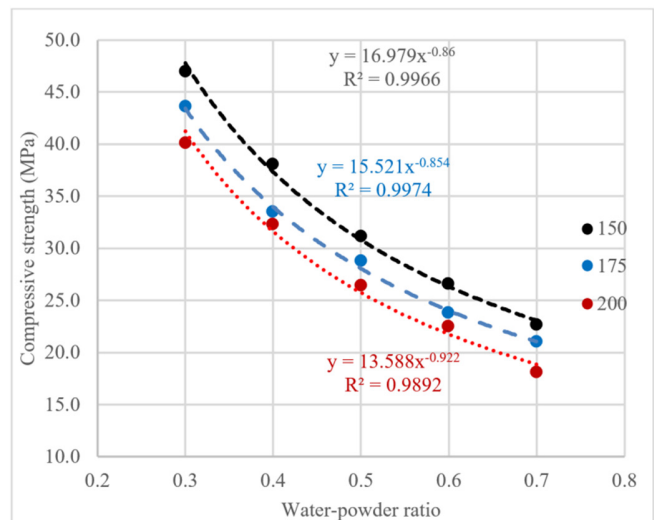


Fig. 9. Water-powder ratio versus compressive strength.

D. Proposed Mix Design for HVFA-SCC

Based on the observations during testing, this study proposes the following steps for the mix design of HVFA-SCC:

1) Determining the Compressive Strength

The proposed mix design can be used for concrete with a compressive strength of 18-47 MPa.

2) Determining Water Content

The water content per m^3 of concrete can be set to 150, 175, and 200 kg/m^3 . If a value between these levels is required, it can be determined using an interpolation formula.

3) Determining the Water-Powder Ratio

The water-powder ratio value can be set using Figure 9 or the relationships in (1-3).

4) Determining Powder Weight

The weight of the powder can be calculated by dividing the water content by the water-to-powder ratio. Also, the weight of cement and fly ash can be taken as 50% of the powder's weight.

5) Determining Concrete Weight

The weight of concrete can be calculated using Table II.

6) Determining Aggregate Weight

The aggregate weight is calculated by subtracting the weight of the powder and water from the total weight of the concrete.

7) Determining the Weight of FA and CA

FA and CA weights can be calculated using the packing density approach. After obtaining the CA/FA ratio from the packing density, the weight of the FA and CA can be calculated by multiplying the CA/FA ratio by the total aggregate weight.

8) Determining the Weight of SP

The weight of SP required is calculated by multiplying the SP percentage by the powder weight. The percentage of SP can be set to 1.2% of the powder weight.

9) Sample Calculation

The sample calculation for 1 m^3 mix design is: Let the estimated compressive strength at 28 days be 28 MPa. For this target strength, the water content can be taken as 175 kg/m^3 . Using Figure 9, the water-powder ratio can be set to 0.5. Next, the weight of the powder can be calculated by dividing the water content by the water-powder ratio = $175/0.5 = 350$ kg/m^3 . For this water-powder ratio, the weight of the cement and fly ash, 50% of powder = 175 kg/m^3 . From Table II, the weight of concrete per $m^3 = 2345$ kg/m^3 . Now, the weight of aggregate = weight of concrete – water content – weight of powder = $2345 - 175 - 350 = 1820$ kg/m^3 . In Figure 2, it can be seen that the maximum packing density occurs at FA/CA 50% so that the weight of FA (50% of the total aggregate weight) = 910 kg/m^3 . Next, the weight of CA can be calculated as 910 kg/m^3 . Finally, the weight of SP = $1.2\% \times 350 = 4.2$ kg/m^3 .

IV. CONCLUSIONS

This study proposes a mix design for High-Volume Fly Ash Self-Compacting Concrete (HVFA-SCC) that incorporates 50% fly ash in the powder content. Laboratory tests were performed on both fresh and hardened concrete. The tests conducted on fresh concrete included the Slump flow, L-box, and V-funnel tests. For the hardened concrete, a 28-day compression test was conducted to evaluate its compressive

strength. From the laboratory test results, it can be concluded that:

- The water-powder ratio affects the characteristics of all test specimens. A higher water-powder ratio increases the slump flow value and the blocking ratio, while it decreases the V-funnel flow time test.
- The compressive strength test results reveal that the greater the water-powder ratio is, the lower is the compressive strength. Furthermore, the higher the water content is, the lower is the compressive strength.

The results of the present study indicate that it is feasible to design an HVFA-SCC mixture, which is self-compacting while also containing higher volumes of fly ash. The resulting HVFA-SCC has a slump flow of 560 ± 726 mm, with a compressive strength ranging from 18 to 47 MPa at 28 days. The findings suggest that the proposed mix design can be used for the concreting of structures in accordance with SNI 2847:2019, which requires the minimum compressive strength for SMRF at 21 MPa.

Future research should investigate HVFA-SCC mixtures containing more than 50% fly ash, additional mechanical properties, and their application in reinforced concrete beams and columns.

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